ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

REPORT NO. 1

PROJECT No. E-108-4

A TECHNICAL STUDY ON THE TRANSFER OF THE ORNL 63-INCH CYCLOTRON TO GEORGIA TECH

By

H. R. BREWER

SEPTEMBER 30, 1957

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I. INTRODUCTION

In 1951 the Oak Ridge National Laboratory was authorized by the Atomic Energy Commission to construct a heavy-particle cyclotron. An accelerator, designated the ORNL 63-Inch Heavy-Particle Cyclotron, was then designed and built by the Electronuclear Research Division of the Laboratory. The first beam was obtained on May 20, 1952 and a productive research program was initiated shortly afterwards[(1)]. The present as well as past usefulness of this cyclotron is indicated by the increasing amount of nuclear data derived from its operation.

The Electronuclear Division of ORNL has now been authorized to construct a new heavy-particle cyclotron to be completed in the fall of 1958 or soon thereafter. Since they plan to center their research activities on the new cyclotron, they are receptive to proposals for relocating the 63-inch cyclotron on some university campus. On the basis of this information, a Station-sponsored project (E-108-4) was initiated to determine the feasibility of locating the cyclotron at Georgia Tech. To further this study, the Oak Ridge Institute of Nuclear Studies granted H. R. Brewer of the Engineering Experiment Station a three-month stay in the Electronuclear Division of ORNL under the Research Participation Program. On the suggestion of Dr. Livingston, Head of the Electronuclear Division, the three months was divided equally between the cyclotron operation and design group, and the physicists and chemist charged with conducting research on the cyclotron. This report presents technical aspects of the cyclotron transfer (costs, transferable components, necessary new components, future research fields, etc.) gleaned from the discussions with these experienced ORNL personnel.

[(1)] A member of the Georgia Tech School of Physics was co-author of the first paper published on research performed with this cyclotron.
Wyly, L. D., and Zucker, A., "Activities in Light Nuclei from Nitrogen Ion Bombardments," Phy. Rev. 89, 524 (January 15, 1953).

II. TWO POSSIBLE MODIFICATIONS OF THE ORNL 63-INCH CYCLOTRON

Parameters of the 63-Inch Cyclotron

The basic design of the 63-Inch is that of a conventional fixed-frequency cyclotron. A description of the machine, complete with pictures of the dee system and ion source, is contained in the literature[(2)]. In the present operation triply charged nitrogen ions are produced by the ion source and are accelerated in a magnetic field of 15,500 gauss. The ions are then electrostatically deflected at the radius of 25.6 inches yielding an external beam of nitrogen ions with a mean energy of around 28 Mev. The RF accelerating system operates at a frequency of 5.1 Mc/sec and employs dee-to-earth voltages lying between 35 and 50 kv.

As discussed in Section IV the dee system of the ORNL 63-Inch cyclotron is transferable although the magnet is not. For this reason, in the modifications discussed below, two different magnetic fields are assumed while the deflecting radius or maximum ion orbit is held constant. The dee stems are a part of the resonant cavity of the cyclotron and, although a "spider" or shorting bar can be moved to increase the frequency, large frequency changes would entail expensive modifications. The effect of changing various cyclotron parameters is given by the fundamental equations for the cyclotron resonant frequency f and for the maximum particle energy E. These are

$$f = \frac{B\ e}{2\pi M} \text{ and } E = \frac{B^2\ e^2 R^2}{2M} .$$

Here, B and R are the flux density and maximum orbit radius of the cyclotron while e and M are the charge and mass of the accelerated particle.

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(2) Livingston, R. S., Nature 173, 54 (1954).

Model I

One promising modification of the ORNL 63-Inch would involve a change in the charge of the accelerated particle. A study of the heavy-ion spectrum of the present ion source indicates an appreciable output of quadruply charged nitrogen ions. Thus, with the present magnetic field, the cyclotron equations above predict that a frequency of 6.8 Mc/sec will be required to accelerate quadruply charged nitrogen ions up to a maximum energy of 50 Mev. The Coulomb barrier of the target nucleus prevents an appreciable number of 28 Mev nitrogen ions from entering nuclei which fall above sulphur in the periodic table. With the projectile energy extended to 50 Mev, the nitrogen ions could enter the nucleus of any element below ruthenium. This would provide an appreciable extension of the research capabilities of the 63-Inch cyclotron. One disadvantage of the 50 Mev modification would be the production of a large neutron flux which in turn would require shielding. However, Dr. A. Zucker of ORNL has recently suggested that coating the inside of the dee system with silver or tantalum would greatly reduce the neutron background.

To provide the 15,500 gauss field assumed for Model I, three alternative magnet systems are discussed in the magnet design section. Two of these magnet systems (the air return Beta magnet and the iron return Beta magnet) utilize surplus Beta coils left over from the wartime mass spectrographs. The third magnet system (Magnet C) is a new construction based on the ORNL 48-Inch magnet design. It is recommended that the Magnet C system be adopted since the savings in the use of the other two magnet systems may not only be small but may be nonexistant.

Model II

The energy of the 63-Inch cyclotron could also be increased by raising the magnetic field from 15,500 gauss to 18,000 gauss. Triply charged nitrogen ions could then be accelerated to an energy of 38 Mev with an RF frequency of 5.9 Mc/sec. This modification would have a higher beam intensity than Model I since the ion source emits in the order of ten charge-three ions for each charge-four ion. Although the 38 Mev nitrogen ion is just past the threshold for penetration of the Coulomb barrier of copper, the neutron flux produced by this beam should be much smaller than the flux generated by the 50 Mev beam of Model I. For this reason shielding is not expected to be an importact factor in Model II.

Again it is recommended that a new magnet system be constructed without using the Beta coils. As the magnetic field is increased it becomes progressively more difficult to smooth out magnetic inhomogeneities by shimming. Thus it is felt that the asymmetrical Beta coils would introduce serious shimming problems in the production of an 18,000 gauss field. Magnet D in Section V is an example of the type of magnet needed to produce the prescribed field. The Model II cyclotron would be slightly more expensive than Model I. The major difference (neglecting shielding) would lie in the cost of the two magnet systems and would be around \$34,000. It is felt that the larger magnet of Model II increases the opportunities for future research programs.

III. RESEARCH POTENTIAL OF THE NITROGEN CYCLOTRON

General Discussion

The use of the nitrogen ion as a nuclear projectile offers unique advantages when compared with lighter particles. As an example, many nuclear energy levels may be excited by a nitrogen accelerator which are not accessible to a proton, deuteron, helium three, or an alpha particle machine. In addition the relatively small number of heavy ion accelerators in existence make research in this field particularly attractive. The ORNL 63-Inch nitrogen cyclotron was the forerunner of several heavy ion accelerators now under construction. However, it is important to note that these newer machines would complement a remodeled 63-Inch machine rather than compete with it since they will operate in a different energy range. There is a lower energy, nitrogen cyclotron (15.6 Mev) presently in operation at the Leningrad Physico-Technical Institute of Sciences, and there are several other accelerators designed to operate above 80 Mev, including the new ORNL 48-Inch cyclotron. The 63-Inch is the only nitrogen accelerator designed to utilize energy ranges around 30 Mev.

The modifications of the 63-Inch discussed in Section II would effect a major increase in the research potential of the cyclotron. Approximate calculations indicate that nitrogen ions with energies of 28, 38, and 50 Mev should be able to penetrate the Coulomb barriers of all elements up through sulphur, copper and ruthenium respectively. An examination of a chart of the nuclides shows that 33, 72, and 133 stable isotopes have atomic numbers equal to or less than these three respective elements. Therefore, compared with the present cyclotron, Model II has roughly twice as many possible nuclear targets while Model I has approximately four times as many. Both modifications require a new magnet and removal of the present asymmetry of the magnetic field should reduce the attenuation in the accelerating orbits by at least a factor of ten. Model II should then have a beam intensity ten times that of the 63-Inch. In addition it is felt that a new magnet, in conjunction with an external focusing magnet, will sharpen the energy definition to perhaps ± 50 kev instead of the present ± 300 kev. If this is realized then transitions to individual nuclear energy levels may be resolved. This possibility of observing individual nuclear energy levels would generate a number of interesting research studies.

The following paragraphs give examples of specific research programs capable of being investigated by the Model I and II cyclotrons.

Study of Nuclear Reactions

The formation of compound nuclei by nitrogen bombardment is characterized by (1) a large angular momentum transfer, (2) an even distribution of projectile energy among the target nucleons, and (3) a resultant compound nucleus with large excitation energy. These three conditions, however, are just those required to apply the statistical model of the nucleus. Therefore, a nitrogen accelerator is singularly well adapted for evaluation of statistical nuclear theories. Future research in this field would be expected to be more or less an extension of studies now underway at ORNL using the 63-Inch cyclotron. Elements below copper (Model II) and below ruthenium (Model I) would be bombarded with nitrogen ions. Measurements of the number and energy distribution of particles evaporated from the resulting compound nucleus would then give information on cross sections for formation of compound nuclei, densities of nuclear energy levels, etc.

An estimation of the importance of nuclear surface phenomena could be obtained for elements below copper (Model I) and below ruthenium (Model II). The distributions of energy and angular momentum would be measured for protons, deuterons, tritons, and alphas arising from nitrogen bombardment of these elements. Interesting comparisons could then be made with the theory of nuclear reactions for a variety of nuclides.

Previous experiments at ORNL using the 63-Inch cyclotron, have uncovered nucleon transfer reactions whereby a nitrogen ion and a target nucleus, may exchange protons and neutrons in a grazing collision. Satisfactory theoretical explanations of this process have not yet been advanced, and more experimental data would be extremely valuable. Either model cyclotron could be used to bombard light elements and observe the angular distribution of heavy particles resulting from this type of reaction. Here it is important to look at the angular distribution of the individual states of the resulting nuclei so that the expected increase in energy resolution of the modified cyclotron will be needed.

In the past, a large amount of our information regarding nuclear forces has come from scattering experiments. It is anticipated that nitrogen scattering experiments will also be informative. For an example, the higher energy nitrogen ion of Model I could be used to investigate the applicability of scattering calculations based upon the optical model of the nucleus.

Coulomb Excitation

Bombardment by charged particles may cause nuclear excitation even though the particles do not actually penetrate the nuclear barrier. This type of excitation, produced by the interaction of the electromagnetic fields of the particle and nucleus, is called Coulomb excitation.

In spite of the known superiority of heavy ions in this process, no work has been done using nitrogen ions, except for a few Russian experiments with their 15.6 Mev nitrogen accelerator. For E2 transitions in Coulomb excitation, nitrogen ions have signal to noise ratios (for background due to bremstrahlung and K-shell excitation) similar to those of alphas. Both ratios are far larger than the corresponding ratios for protons. Choosing an optimum energy for each particle so that these signal to noise ratios are maximized, the cross section for E2 excitation using nitrogen ions is approximately 12 times the cross section for alphas and 123 times the cross section for protons.

Coulomb excitation has proven to be a most valuable aid [(3)] in investigating the rotational energy levels of collective nuclear motions. Alphas and protons have been the principal projectiles used. However, due to their heavier mass, nitrogen ions could be used to observe rotational energy levels via Coulomb excitation which would not be detected with either alphas or protons. Thus in spite of the amount of previous work it is felt that either Model I or II could make significant contributions in studies of rotational states.

The cross section for exciting higher order nuclear rotational states is an increasing function of projectile mass. Thus there is a possibility of using nitrogen ions to investigate second order processes such as a reorientation of nuclear spin during the excitation and double E2 excitations of $I = 4$ states. These two effects would be difficult or perhaps impossible to observe if lighter particles were used.

In collective motions of nuclei, the rotational levels corresponding to preservation of the nuclear shape have been the subject of many studies. However, the collective motion of the nucleons should also give rise to higher energy levels corresponding to changes of the nuclear shape. These vibrational

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[(3)] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. 28, 432 (1956).

energy levels have been roughly estimated for even-even nuclei as one Mev for quadrupole vibrations and several Mev for octupole vibrations[3]. Any estimation of the cross section for excitation of these vibration levels will depend on the unknown nuclear transition probabilities. However crude calculations indicate that the nitrogen ions of Model I are above the energy threshold for an observable yield of quadrupole excitations but are below the corresponding octupole threshold. The ion energy of Model II is too low to excite these vibration levels. Since future experimental studies of nuclear vibrational levels will provide crucial information on nuclear structure, research in this field should be considered in any modification of the ORNL cyclotron.

Atomic Physics

Models I and II would have research application in the field of atomic physics. Research has been performed at ORNL on the response of scintillation counters to nitrogen ions as a function of ion energy. This study could be extended to other ions by the "knock-on" process. In addition papers have been published by the staff of the 63-Inch cyclotron on the range-energy relations of nitrogen in nickel and the equilibrium charge distribution as a function of energy for nitrogen ions in Formivar. Similar investigations could be conducted using different elements and materials.

Internal conversion coefficients may also be measured by Coulomb excitation of the nucleus using nitrogen ions. A few conversion coefficients have been measured in this manner with sufficient accuracy to show finite nuclear size effects. Alpha particles were used in the previous case[4] but nitrogen ions would have the same signal to noise ratio and at the same time increase the yield of converted electrons.

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(4) McGowan, F. K., and Stelson, P. H., Phy. Rev. 103, 1133 (1956).

Radiochemistry

The use of a cyclotron in radioisotope production would make possible the preparation of carrier-free radioisotopes, including many isotopes which cannot be obtained from a reactor. In particular, the Model I cyclotron would make possible the production of radioisotopes from all the elements up to ruthenium which would, in effect, provide the radiochemist with prototypes of all the elements of the Periodic Table. This means that tracer studies of such phenomena as the complex-forming properties, crystal isomorphism, redox potentials, sorption behavior, solubilities, hydrolytic behavior, et al., could be carried out with representative members of all the families and groups of elements.

The production of radioisotopes for use in nuclear decay scheme studies is an important research area which deserves special mention. Here the chemist has a two-fold interest, being obliged to evolve intricate and often unique separations processes to insure radioisotope purity, and at the same time to perform the decay scheme studies themselves. Many of the radioisotopes of interest in decay scheme studies can most conveniently be made with an accelerator of the type under discussion.

Finally, use of highly charged, high-energy particles makes possible an extension of the field of radiation chemistry. Creation of high density ion tracks by such charged, heavy particles should permit the chemist to sort out the contributions caused by the high ion and radical densities from the gross effects observed with less highly ionizing radiations.

Miscellaneous

There would no doubt be many more research fields open to a Georgia Tech nitrogen ion cyclotron than have been discussed above. To mention a few, either modification of the 63-Inch cyclotron could be used to study radiation damage to materials by heavy ions and fast neutrons. Biophysical research could be conducted on tissue damage caused by heavy ion irradiation. The local production of radioactive isotopes would also be useful for research outside the field of radiochemistry. As an example, members of the physics department are currently conducting investigations of nuclear energy levels using radioactive isotopes which have a sufficiently long life to survive shipment. At present the 63-Inch has so low an energy that relatively few, low Z isotopes are produced, but if the energy of the machine were increased as in Model I, the projectiles would be able to penetrate the nuclear barriers of elements up to ruthenium. The short lived radioisotopes so produced would be useful in extending the existing nuclear level studies.

IV. CONVERSION OF 63-INCH COMPONENTS

Magnet

At present the cyclotron's dees are inserted in one of the vacuum banks of a huge Beta Calutron "race track" magnet and there is no possibility of transferring the existing magnet. The magnetic field has a flux density at the center of 15,500 gauss and has a linear two percent fall-off in the radial direction to provide magnetic focusing. The original Calutron magnetic field was not radially symmetric so that extensive shimming operations were required to produce the present modification. A sharp attenuation (around 99 percent) occurs in the beam at approximately two-thirds of the deflecting orbit radius. This attenuation is attributed to a distortion of the magnetic median plane and it is thought that a properly designed magnet would increase the beam intensity by at least a factor of ten. The difficulty involved in changing the symmetry of a magnetic field by shimming is one of the reasons for not using the asymetrical Beta coils to drive the magnet of the Georgia Tech cyclotron. Four possible magnet systems are discussed in Section V.

Oscillator and Transmission Lines

The RF accelerating voltage feeding the system is supplied by a one tube grounded grid oscillator using a 100 kilowatt power triode (RCA 5770). The oscillator and transmission lines are enclosed in separate metal cabinets mounted on wheeled dollies. The present cyclotron frequency is about 5.1 Mc. The oscillator and transmission lines are transferable and retuning these components to match the new resonant frequencies of Models I and II is not expected to be a major change.

Dee System

The dee system comprising the dees, dee stems, dee stem housing, face plate, and liner could be transferred intact. The plane of the dees is vertical in the 63-Inch cyclotron and for structural reasons any accelerator utilizing this dee system would have to be a vertical cyclotron. Models I and II for a modified 63-Inch cyclotron would require retuning the dee system to RF frequencies of 6.8 and 5.9 Mc/sec, respectively. No serious difficulties are expected with either of these frequency changes.

Vacuum Tank

The vacuum tank enclosing the dees is fitted to the "D" shaped Calutron magnet and would not be suitable for a conversion employing circular magnet pole tips.

Diffusion Pumps and Manifold

The manifold tank provides a transition from the dee system vacuum tank into two 20-inch oil diffusion pumps which are mounted in parallel and backed by two 8-inch oil diffusion pumps. The entire system is movable and the crating, shipping and installation expenses should be much less than the cost of new equipment. The average life of the surplus oil diffusion pumps was purported to be extremely long and the maintenance costs were represented as negligible. The ion source enters the dee system via a vacuum lock installed in the manifold tank and the cyclotron beam leaves through an additional vacuum lock on the same tank. For these reasons it is recommended that design parameters of any new vacuum tank should be adapted to the present manifold tank.

Fore Vacuum System

The differential between atmospheric pressure and the much lower exhaust pressure of the oil diffusion pumps is maintained by the fore vacuum system.

This consists of two mechanical Kinney pumps, having fifteen and two horsepower respectively. The system is designed so that the two pumps may be used either in tandem or separately. The system (or one which is identical) is transferrable and a saving of some $10,000 [5] could be expected using the existing equipment.

Ion Source, Probe, and Vacuum Lock

If the present manifold system is transferred then the ion source, probe and vacuum lock could be used without modification. A hot cathode ion source is in use now. Although the mean life of the source is only about 7.5 hours, the time required for a source change with the present system is only about 30 minutes.

Much development work has been done at ORNL on hollow anode sources with estimated mean lives of 20 hours. So far these sources have been very unstable with uninterrupted running times in the order of minutes. Thus while the hollow anode source may be potentially a better device, much development work remains, and it is recommended that at first the existing source be used.

Control Instrumentation

The control instrumentation section includes an array of protective interlocking relays as well as the actual meters and controls on the console itself. These components are transferrable; however, extensive wiring modification will be required due to the introduction of different equipment such as power supplies, magnet, electric utilities, water cooling system, etc. As a minor consideration the present control panel has the appearance of being a veteran of many alterations and is not exactly a show piece. Installation of the old equipment at Georgia Tech was estimated by the design group to lie between $10,000 and $15,000.

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(5) Oak Ridge National Laboratory, "Proposal for a 48-Inch Heavy-Particle Cyclotron." February 1955.

Magnet Power Supply

At present a 1750 kilowatt motor generator supplies dc current to drive the Calutron magnet for the 63-Inch cyclotron. It is much larger than is required and due to its usefulness for other ORNL projects would not be released.

The power and current required to produce a given magnetic field depends strongly upon the design parameters of the magnet. For this reason the motor generator, iron magnet yoke, and coils are considered as a unit in the magnet design section and the magnet dimensions are chosen so as to minimize the initial cost of the system.

Further discussion of the requirements and cost of the magnet power supply are contained in the section on magnet calculations.

Arc Voltage Power Supply

The hot cathode ion source now in use requires that the electrons emitted by the cathode be accelerated by a 400 volt potential drop on entering the nitrogen ionizing chamber. For stable operation of the source, the arc voltage power supply must furnish around 3 amps at 400 volts. Since power supplies of this type were components of the wartime mass spectrograph installation, they are readily available. Whether it is less expensive to build anew rather than to renovate old equipment is not known; however, the cost of new equipment is expected to be under $1,500.

Dee Bias Supply

The cyclotron dees and stems have a negative bias of approximately 1000 volts to eliminate ion loading difficulties. The current required is only around 150 milliamps. This supply will not be transferred but it is comparatively inexpensive and could be purchased for $700.

Oscillator Power Supply

The oscillator requires a power supply furnishing 10 kilovolts with a current between 6 and 7 amperes. A number of Beta M power supplies, housed in rather large cubicles, are connected in parallel to form the present installation. Although undoubtedly a sufficient quantity of these surplus supplies could be obtained to feed the oscillator, the cost of housing and renovating this equipment might be several times greater than buying new equipment. The existing power installation occupies a much larger floor space area than would be required for commercially available equipment. A General Electric representative gave an unofficial estimate of under $10,000 for a commercial power supply.

Ion Source Power Supply

The ion source requires a current of approximately 350 amps at 6 volts. The present power supply is a General Electric Type-K-rectifier and ORNL has many of these in surplus storage. The cyclotron design group at ORNL roughly estimated the cost of setting up one of the surplus K supplies at Tech at $5,000. This figure seems rather large since no major modifications are required. Furthermore the estimated cost of new equipment is $2,000.

Pending a more careful analysis, this component should be considered transferrable.

Beam Deflector Power Supply

The cyclotron beam is extracted by an electric deflecting field. The RF voltage required on the deflecting plate is 50 kilovolts and the current drawn is approximately 8 milliamps. The present power supply is a part of the ORNL cubicles mentioned under the oscillating power supply section. The Beta G supply could probably be used without modification; however, the cost of stripping this equipment from old cubicles plus renovation and installation costs were crudely estimated to be around $10,000 by ORNL cyclotron design group. If this figure is realistic then it would perhaps be cheaper to buy or to build a new supply.

V. MAGNET DESIGN

Introduction

Since the present cyclotron magnet is not transferrable, a new one would be required. A large number of Beta coils are surplus items at Oak Ridge, being left over from the wartime mass spectrographs. Dr. Livingston, head of ORNL Electronuclear Division, suggested the possibility of either a loan or a gift from the AEC of several of these Beta coils and recommended an investigation of the possible saving in using these coils. Therefore, two alternative schemes utilizing these Beta coils are presented below under the headings Magnets A and B. The sections labeled Magnet C and D consider designs and costs for entirely new constructions.

The shape of a Beta coil is basically rectangular, 80 inches by 60 inches, with one corner truncated by a 45 degree slice reducing the small side to 42 inches. Each coil is oil cooled and consists of 174 turns of a copper bar having a cross-sectional area of 1.26 square inches.

Magnet A (Air Return Beta Magnet)

If the AEC would release six or eight of these Beta coils then perhaps the least expensive method of producing a magnetic field for the 63-Inch cyclotron would be an open ended magnet. The Beta coils could be filled with iron to confine the flux in the center gap leaving an air return path for the flux. The total reluctance of the magnetic flux circuit would be greatly increased over that of an iron return path so that the ampere turns required would be increased. Thus the power required to operate the magnet would be larger and the initial cost of a motor generator supply would increase.

A study of this type of magnet has been made by R. S. Lord and E. D. Hudson of the Electronuclear Division of ORNL and using the Beta coils, it appears quite possible to generate the field required for the 63-Inch cyclotron by this method. Magnet A would require in the neighborhood of twice the power of Magnet C; therefore the cost of the motor generator of system A should be about twice the cost of the motor generator of system C, i.e., $100,000. If the additional expense of filling the Beta coils with iron is then considered, the cost of system A should not be far below that of Magnet B ($125,000).

The use of the Beta coils would also introduce the following expenses. Since the other components of the 63-Inch are water cooled, a separate oil cooling system would be necessary for the Beta coils. There is always a fire risk with oil cooling systems and at least one cyclotron has been lost this way. The Beta coils are not circular therefore an extensive shimming operation would be necessary to give the magnetic field azimuthal symmetry.

Magnet B (Iron Return Beta Magnet)

A second magnet system based upon acquisition of the Beta coils would be to build a magnet yoke having an iron return path but use the old Beta coils to drive the new magnet. This system would have a much smaller power requirement than A and due to the use of copper coils in place of aluminum it might be slightly less than C.

Relative to the C system, B would have additional costs due to the following. As mentioned in the preceding section, the Beta coils would require an oil cooling system. The size and shape of the Beta coils would require more iron than C, assuming the yoke design of C is employed. The lack of circular symmetry in the Beta driving coils would require a greater effort in shimming the pole faces. For these reasons it is felt that a minimum cost of the B system would be the cost of the optimized C system less the cost of the C coils. This yields a cost estimate of Magnet B of around $125,000.

Magnet C (Model I New Magnet)

The Electronuclear Research Division, at ORNL, is building a 48-Inch heavy ion cyclotron using a magnetic field of 20,000 gauss. The yoke configuration assumed (Figure I, page 23) for the Model I cyclotron magnet is modeled after the ORNL 48-Inch magnet although pole diameter, pole shape, gap width, and field strength have been changed. The ratio of the width to the depth of the rectangular flux return path has been made the same as the 48-Inch to preserve the strucural strength of their yoke. The magnet design was undertaken to provide a realistic cost estimate and, as such, has escaped the more rigorous treatment of a construction model.

In the Appendix, a set of the required parameters of the magnet is fixed and a cost equation is derived for the magnet system comprising the coils, yoke, and motor generator set. The cost is shown to be a function of the current density in the coils and various constants. Figure III in the Appendix gives a graph of cost versus current density and indicates a minimum cost of $151,000 for the system. The current density corresponding to this minimum cost then determines the coil size and thus the overall magnet size as well as the power needed to supply the magnet. In this way a minimum cost system subject to the fixed constraints, is designed.

The magnet yoke dimensions established by the minimum cost are given in parenthesis in Figure I. Other parameters of Magnet C are listed below.

Pole Face Diameter	69.2 inches
Field at Center	16,000 gauss
Exciting Current	4.85×10^5 amp. turns
Cost of Materials	$151,000
Magnet Yoke	
Cost	$76,000
Weight	152 tons
Coils, Aluminum	
Cost	$26,000
Weight	5.2 tons
Motor Generator Set	
Cost	$49,000
Power	245 kilowatts

Magnet D (Model II New Magnet)

A magnet was designed for the Model II modification of the ORNL 63-Inch cyclotron similar to the Model I magnet. The fundamental change involved increasing the field to 18,000 gauss and the attendant increase of the pole diameter to 75.2 inches. An examination of a graph of cost versus current density similar to Figure III in the Appendix yielded a minimum cost of $185,000 for Magnet D and a set of dimensions shown on Figure II, page 24. The principal parameters of the Model II magnet system are given below.

Pole Face Diameter	75.2 inches
Field at Center	18,000 gauss
Exciting Current	5.45×10^5 amp. turns
Cost of Materials	$185,000

Magnet Yoke		
	Cost	$93,000
	Weight	185 tons
Coils, Aluminum		
	Cost	$31,000
	Weight	6.2 tons
Motor Generator Set		
	Cost	$61,000
	Power	300 kilowatts

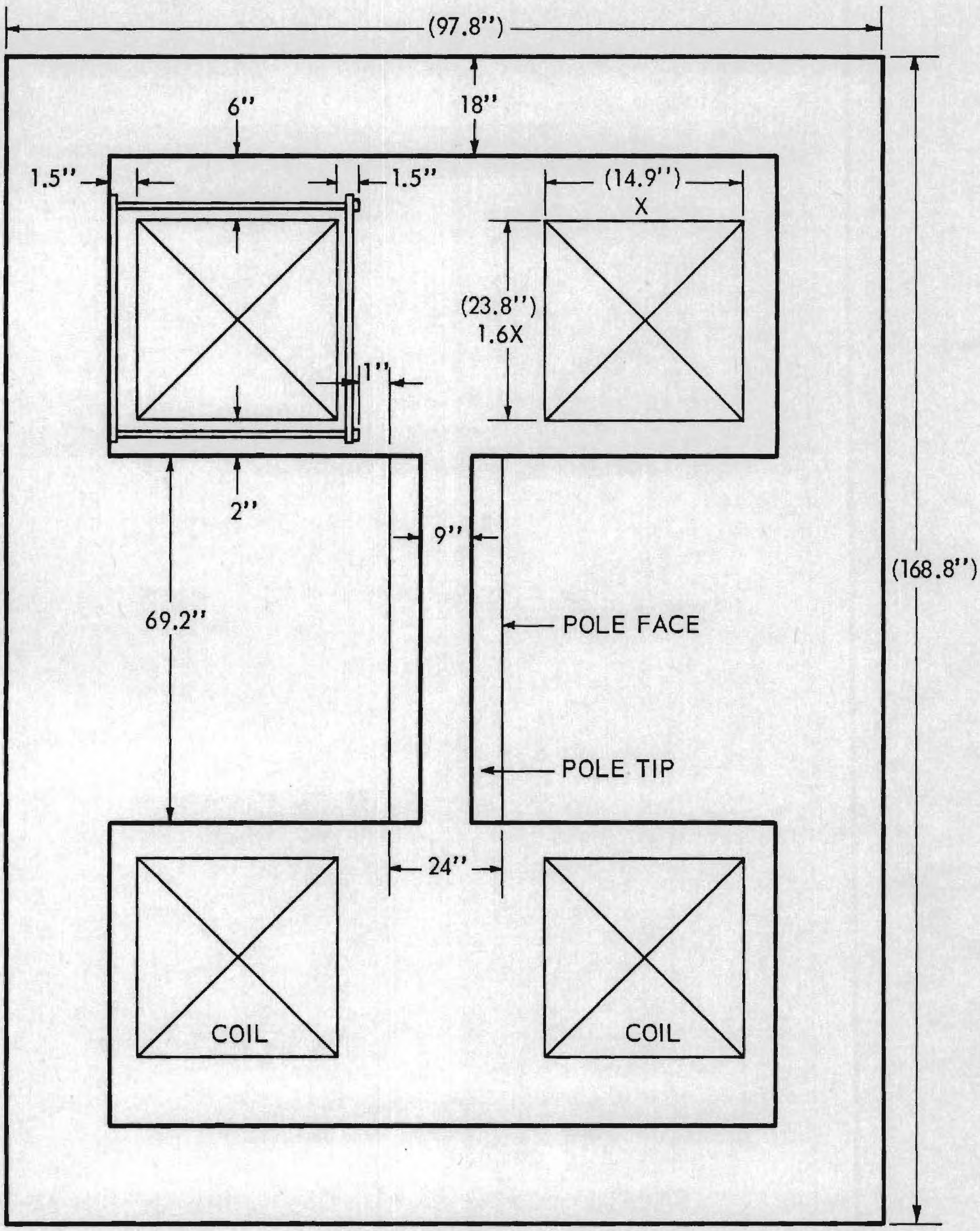

Figure I. Vertical Cross Section of Magnet C. (Dimensions Shown in Parenthesis were Obtained from Minima of Magnet C Cost Curve Given in Figure III).

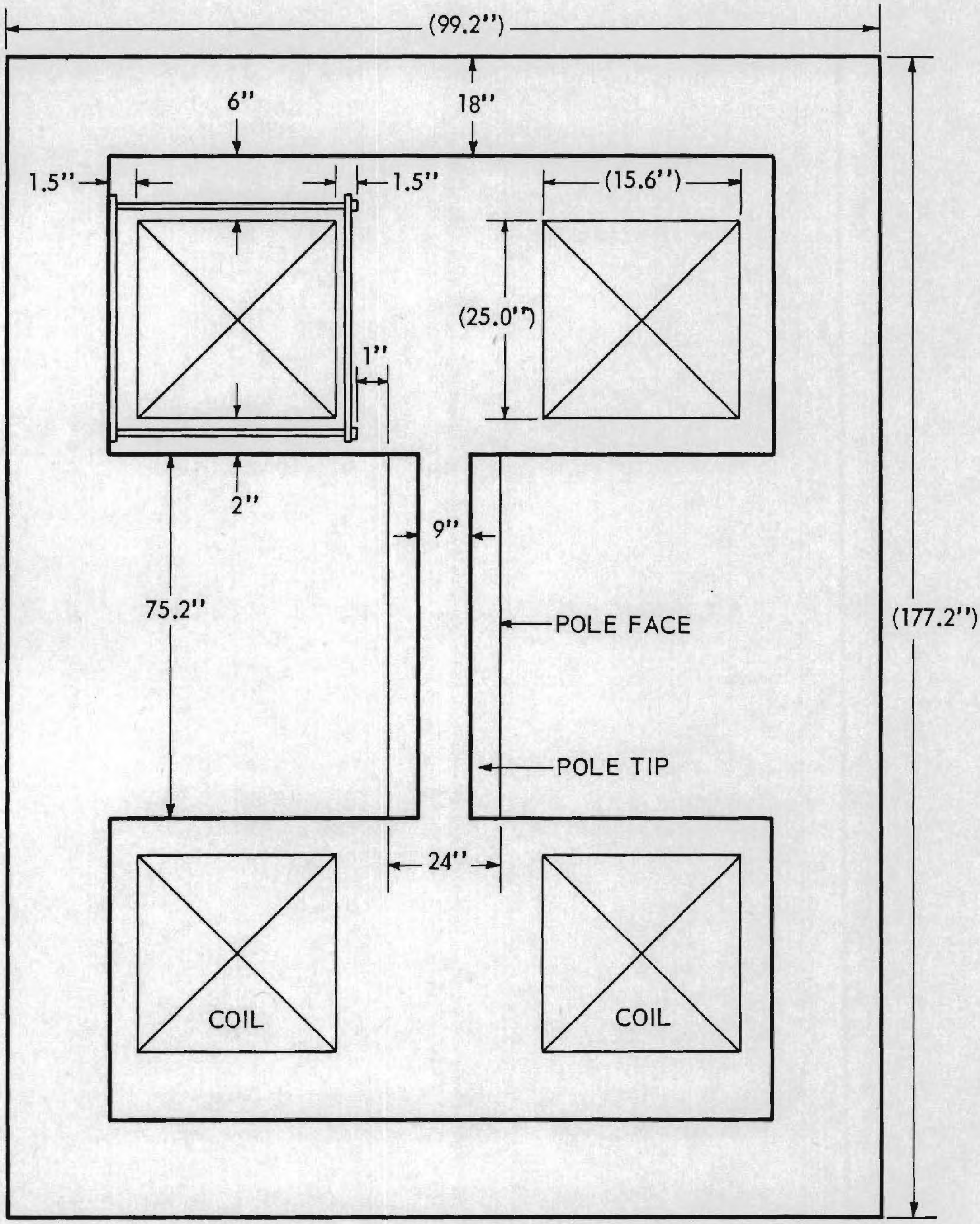

Figure II. Vertical Cross Section of Magnet D. (Dimensions Shown in Parenthesis were Obtained from a Cost Curve for Magnet D Similar to the One Shown in Figure III).

VI. REQUIREMENTS FOR THE CYCLOTRON INSTALLATION

Introduction

This section presents estimated costs of the entire cyclotron installation together with a suggested operating staff. It is thought that the estimated cost parameters of the cyclotron components are near minimum requirements. However, an adequate cyclotron research program could be initiated even if considerable reductions were made in the requirements for the building and auxiliary research equipment. Thus these last two estimates should be considered as goals to be attained rather than necessary minimum requirements.

Cyclotron Building

In addition to the areas suggested below, the cyclotron installation will require a chemistry laboratory near the cyclotron itself. Since both the Reactor and Radioisotope Laboratories have these facilities, it was thought the cyclotron would be housed in an addition to one of these buildings. The cost of shielding is omitted in the building estimate since it will depend on the building design and on the type of cyclotron recommended.

Cyclotron room (25' ceiling)	50' x 20'	1000 sq. ft.
Research working area	25' x 60'	1500
Service area	20' x 30'	600
Power supply room	20' x 20'	400
Counting area	15' x 20'	300
Control room	15' x 20'	300
Staff offices (5 each)	150 sq. ft.	750
Service personnel	15' x 15'	225
		5,075 sq. ft.

Cost at $30 per sq. ft. $150,000

Auxiliary Equipment

Since the cylcotron by itself is not a complete research tool, a preliminary list of the more expensive auxiliary equipment has been compiled as shown. It is felt that this research equipment is necessary to exploit the research potential of the cyclotron as described in Section III.

Analyzing Magnet	$20,000
Multichannel analyzer	20,000
Geiger counters, amplifiers rate counters, etc. for half life determinations	10,000
Helium leak detector	3,500
3 Oscilloscopes	4,500
Coincidence setup including, miscellaneous scalers, linear amplifiers, and detectors	17,000
	$75,000

Detailed Costs

A detailed description of the individual cyclotron components is given in the Component Section and in some cases the basis for estimating costs is also given. The Electronuclear Research Division of ORNL has published a report (5) in which they investigated the cost of converting their 44-inch proton cyclotron into a 48-inch nitrogen accelerator at a different location. Since their problem is very similar to moving the 63-inch machine to Georgia Tech, some of their cost estimates were applicable. The estimated costs taken from this report are indicated below by an asterisk.

Magnet, System C	$151,000
15 percent Engineering	23,000
*Oscillator and Transmission Lines	5,000

*Dee System	3,000
*Vacuum Tank	21,000
*Diffusion Pumps and Manifold	7,000
*Fore Vacuum System	12,900
*Ion Source, Probe, and Vacuum Lock	2,000
Control Instrumentation	15,000
Arc Voltage Supply	1,500
Dee Bias Supply	700
Oscillator Supply	10,000
Ion Source Supply	2,000
Beam Deflector Supply	5,000
Total	$259,100
Estimated Cost Rise for 2 years	40,900
Cost of Cyclotron alone	$300,000
Cyclotron Building	150,000
Auxiliary Equipment	75,000
Contingencies	75,000
Total Estimated Cost of Cyclotron Installation	$600,000

Operating Staff

The suggested cyclotron operating staff outlined below is based upon the existing personnel now used at ORNL.

Rank	Number of Personnel	Time Allotted for Project
Experimental Physicists	3	1/2 time
Radiochemist	1	1/2 time
Operating Engineer	1	Full time
Electronics Technician	1	1/2 time
Mechanic	1	Full time
Graduate Student or Technician	1	Full time

The physicists and the radiochemist would be responsible only for the design and execution of research programs. Maintenance and operation of the cyclotron would be the responsibility of the operating engineer, who would be assisted by a technician (graduate student). The mechanic would be employed building cyclotron parts and research equipment, while the primary duties of the electronic technician would be the upkeep of the research equipment, oscilloscopes, multichannel analyzer, etc.

Respectfully submitted:

H R Brewer

H. R. Brewer
Project Director

Approved:

J E Boyd

J. E. Boyd, Director
Engineering Experiment Station

VII. APPENDIX

Assumed Parameters of a New Magnet for the Model I Cyclotron

The fixed dimensions shown in Figure I were chosen as follows:

1. Pole diameter = 69.2 = 2 (final ion orbit radius + gap width).

This value for the pole diameter was taken from a University of California Radiation Lab study entitled, "Sid Magnet Model Test Results" and should allow a two percent fall off for the field from the center to the final ion orbit.

2. The 9 in. pole gap was chosen to fit the present dimensions of the 63-Inch dee system plus 3 in. of additional space to allow for future expansion.

3. The various odd dimensions around the coils were recommended by the cyclotron design group at ORNL to give room for securing the coils to the magnet yoke.

4. The area of flux return path is adjusted to be equal to the pole face area.

5. The thickness (18 in.) of the horizontal yoke sections was chosen so that the ratio of width to depth of these sections would be the same as the 48-inch magnet. The depth of the yoke sections is then 104.4 in.

6. The thickness of the pole tips or rather the distance of 24 in. between pole faces was chosen to insure that the 22 in. wide dee stem housing could enter between the coils.

7. The ratio of 1.6 to 1 for the rectangular cross section of the coils was assumed upon the suggestion of the ORNL group that this would be a near optimum value.

8. The required flux density was taken as 16,000 gauss to simulate the present operating field.

Constants

The following constants used in the analysis are listed below for reference. The cost parameters listed were obtained from ORNL cyclotron group as of February 1957 and are expected to rise at least 5 percent per year.

$1.6x^2 (in)^2$ = cross sectional area of coil

A = pole base area (Sid report) = 3.76×10^3 in^2

S_i = density of iron .284 lb/in^3

k_i = cost of fabricated iron = \$0.25/lb

S_{al} = density of aluminum = .0975 lbs/in^3

k_{al} = cost of aluminum (wound into coils) = \$2.50/lb

ρ_{al} = resistivity of al = 1.22×10^{-6} ohm in

k_g = cost of motor generator installed plus base

= \$200.00/kilowatt (based on 400 kw. G.E. set)

F = coil form factor = ratio of conductor area in coil to total coil area. The latter considers water cooling pipes, insulation, etc.

= 1/2 from ORNL 48-inch cyclotron

η = magnet efficiency = $2.02\ B_c \ell/NI$

= .6 from ORNL 48-inch calculations.

where

B_c = flux density at the center in gauss

ℓ = gap width in inches

NI = ampere turns

η would be unity if the magnet had no fringing field and if the reluctance of the flux return path were small compared with the gap reluctance.

Cost Analysis of Magnet C

Using the symbols and constants given above and the fixed dimensions given in Figure I, the cost of each component may be computed.

Volume of poles $= 2A\,(X + 11.5 \text{ in.})$

Cost of poles $= 2A\,k_i S_i\,(X + 11.5 \text{ in.})$

Volume of vertical yokes $= 2A\,(1.6X + 60.6 \text{ in.})$

Cost of vertical yokes $= 2Ak_i S_i\,(1.6\,X + 60.6 \text{ in.})$

Volume of horizontal yokes $= 2A\,(X + 16 \text{ in.})$

Cost of horizontal yokes $= 2A\,k_i S_i\,(X + 16 \text{ in.})$

Total cost of iron $= A\,k_i S_i\,(7.2\,X + 176.2 \text{ in.})$

Volume of (1) coil $= X\pi\,(2.56\,X^2 + 117.1 \text{ in. } X)$

Cost of coils $= 2F\,k_{al} S_{al}$ (volume of one coil)

$= k_{al}\,S_{al}\,\pi\,(2.56\,X^3 + 117.1 \text{ in. } X^2)$

Power dissipated in 2 coils $= \rho\,J^2 \pi\,10^{-3}\,(117.1 \text{ in. } X^2 + 2.56\,X^3)$ kilowatts

Cost of motor generator set $= k_g\,\rho\,J^2 \pi\,10^{-3}\,(117.1 \text{ in. } X^2 + 2.56\,X^3)$

Material cost of Magnet, coil, and M.G. set

$$= k_i S_i A(7.2\ X + 176.2\ \text{in.})$$

$$+ k_{al} S_{al} \pi\ (117.1\ \text{in.}\ X^2 + 2.56 X^3)$$

$$+ k_g \rho J^2 \pi\ 10^{-3}\ (117.1\ \text{in.}\ X^2 + 2.56\ X^3) \qquad [1]$$

For a parallel flux magnetic circuit we can write

$$NI = \text{amp. turns} = \left(\frac{L}{\mu A}\right) + \left(\frac{\ell}{A}\right) \phi \doteq 2.02\ B_c \ell$$

where B_c is in gauss, ℓ in inches, and Ni in ampere turns.

$$NI \text{ required} = \frac{NI}{\eta} = \frac{2.02\ B_c \ell}{\eta} = 4.85 \text{ X } 10^5 \text{ amp. turns}$$

$$\eta = \text{efficiency} = .6$$

Now considering the current through the cross sectional area of two coils, we have

$$NI = I_T = (2F\ 1.6\ X^2)\ J = 4.85 \times 10^5 \text{ amp}$$

$$\therefore X^2 = 3.03 \times \frac{10^5 \text{ amp}}{J}\ ;\ X = 5.5 \times 10^2 \sqrt{\frac{\text{amp}}{J}}$$

Now substituting these values of X in equation [1], evaluating the constants, and changing J to units of kiloamps/in^2, the final cost in dollars is obtained

$$\text{Cost} = 10^4 [4.7 + \frac{1.03}{J^{\frac{3}{2}}} + \frac{3.35}{J^{\frac{1}{2}}} + \frac{2.72}{J} + 1.04\ J^{\frac{1}{2}} + 2.72\ J] \qquad [2]$$

A plot of equation [2] is shown in Figure III on the following page.

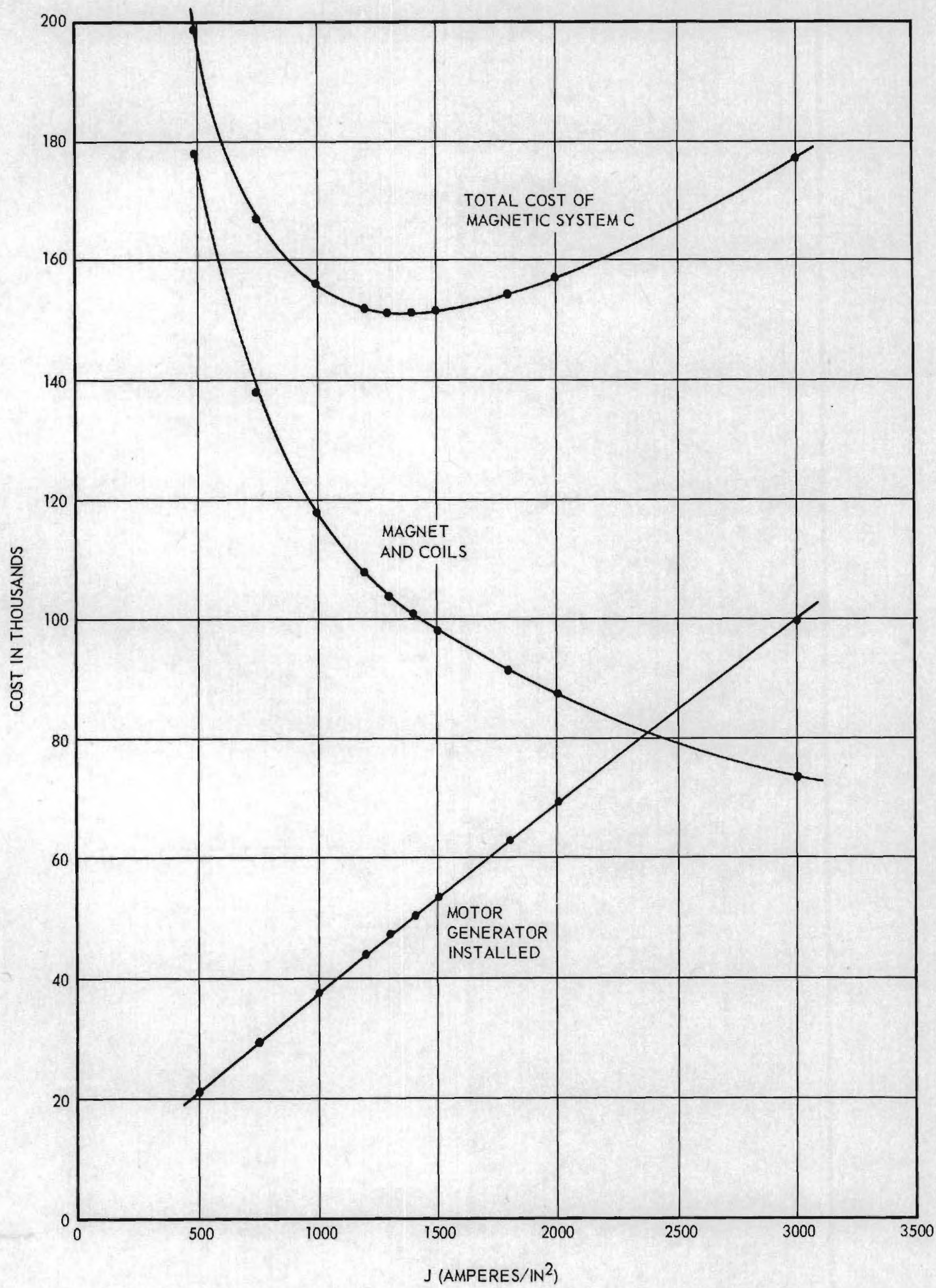

Figure III. Cost of Components of Magnet System C Versus Current Density in Coils.